MINOS Timing and GPS Precise Point Positioning

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for the International Workshop on Accelerator Alignment 2012 in Batavia, IL

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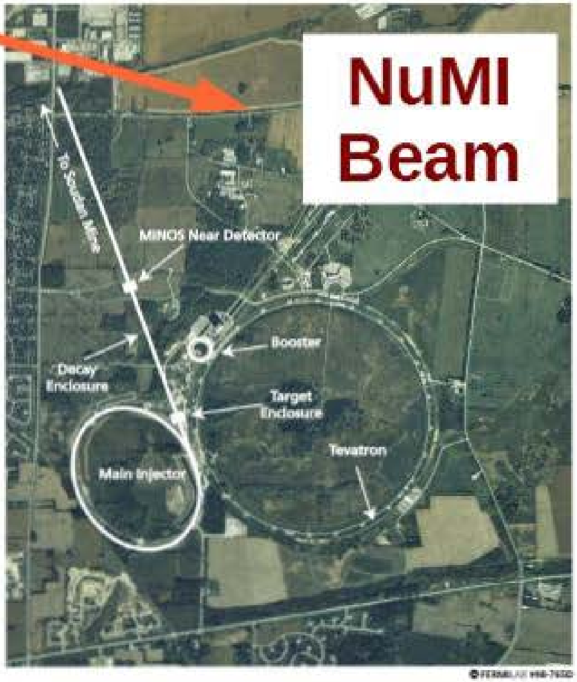
The MINOS Experiment



Detectors consist of alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field

735 km baseline

A Joint USNO-NIST Collaboration

MINOS TIMING

Minos Timing Spec

- Neutrinos created in bunches separated by 19 ns
- ~ 1 neutrino/day detected in Soudan Mine
  - 2 milliseconds travel time
- Must know which bunch created the observed neutrino
- Bunches are about 6 ns wide
  - To become 3.5 ns wide after planned upgrade in 2013
- Therefore want 1 ns RMS   **ALWAYS**

What Kind of Clocks for 1 ns spec?

- Rubidium
- Standard Performance Cesium
- High Performance Cesium
- Maser

Considerations

- Stability
- Cost
- Environmental requirements
- Reliability
- Delivery time
  - Fermilab ordering latency <2 weeks!

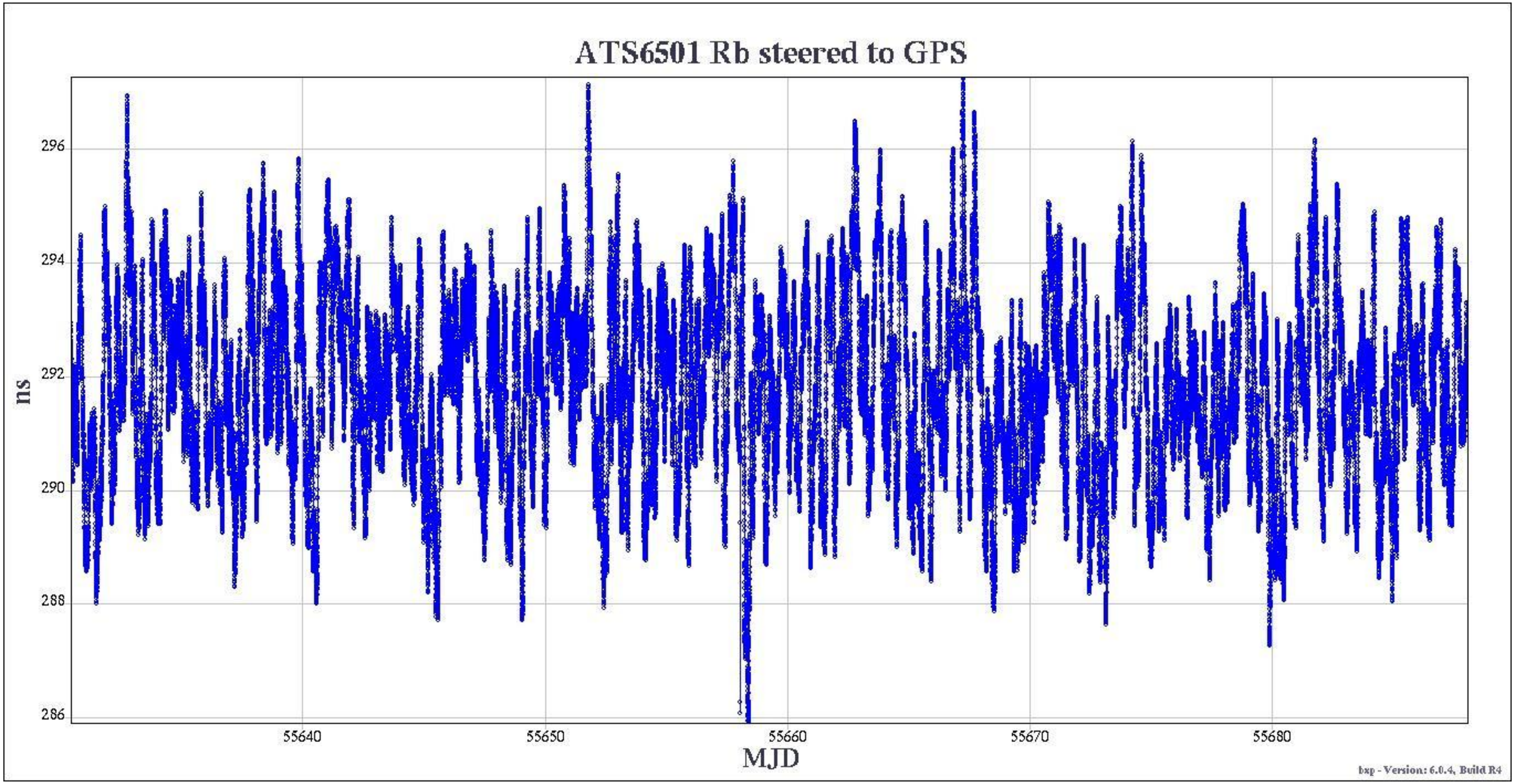
Time Transfer Options

- GPS
  - Direct access (code) - too noisy
  - Precise Point Positioning (PPP)
    - Carrier Phase
    - Best way for day-to-day
    - NIST has supplied 6 NovAtel receivers
- TWSTT – Important for calibration
  - USNO has a specially designed SUV
- Fibers
  - IEEE1588 or pure tone with out-of-band calibration
  - No low-cost Fermilab to Soudan Mine connections known
  - Not yet tested for operational time transfer

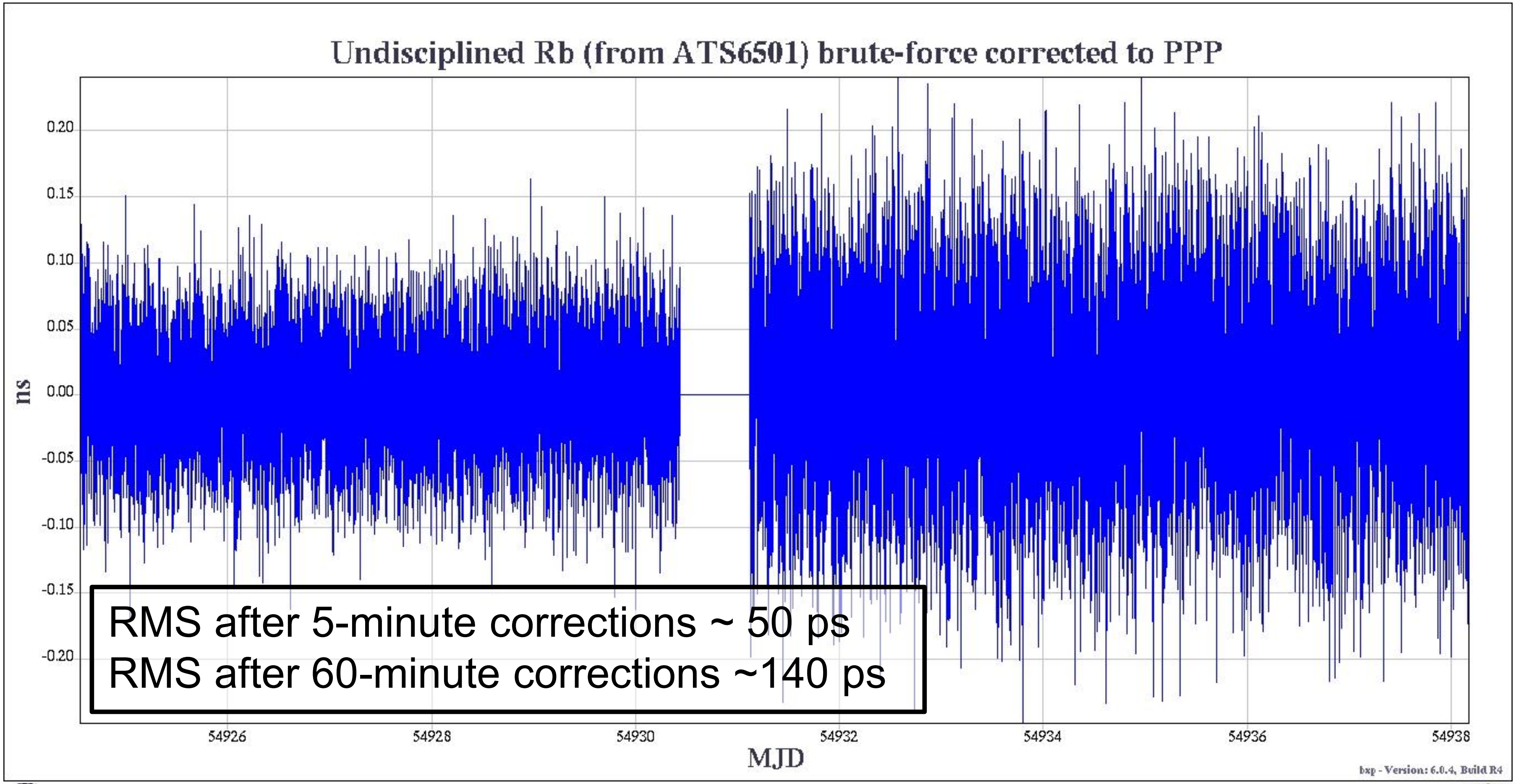
Clock Options

- High-Performance Cesiums
  - A good cesium on a bad day varies 5 ns (2-sigma)
  - Cost ~ $70K each
  - Tube Warranty: 5 years
  - Short-term stabilities ~ square root(tau)
    - In one hour, the two sigma time deviation is ~ 1 ns
- Standard Performance Cesiums
  - 2-3 times noisier than high performance units
  - 12 year warranty
- Rubidiums
  - Super-fancy: Fiber connections & GPS-disciplined, $20K
  - Excellent: GPS disciplined rubidiums $5K-10K
  - Good: free-running rubidiums: $2-5K

GPS-Disciplined Rubidium RMS=1.6 ns



Undisciplined ATS6051 corrected with PPP



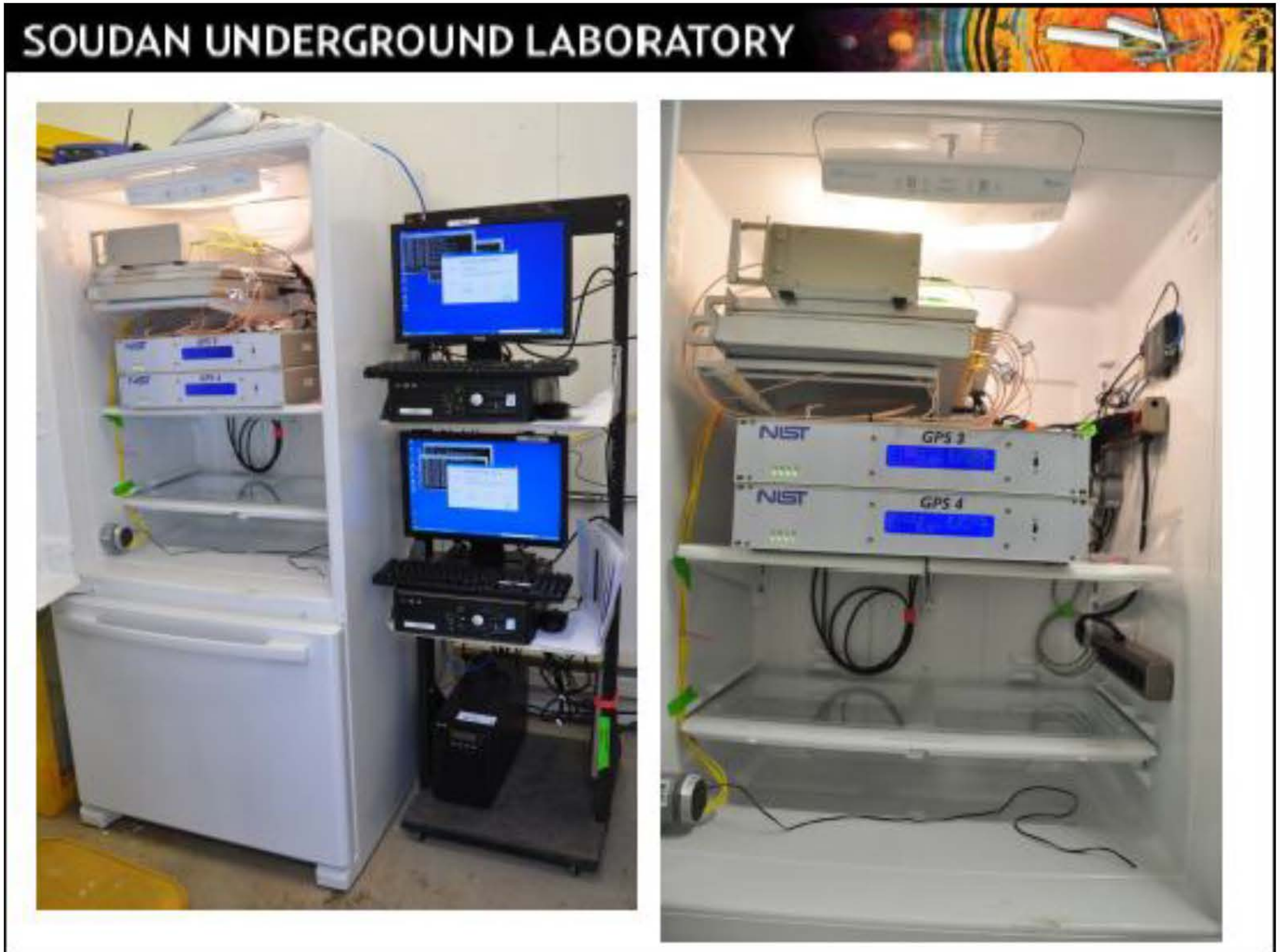
Clock and Time Transfer Conclusions

- Rubidiums corrected with PPP data will meet specs
- But standard-performance cesiums have benefits
  - Longer holdover time
  - Variations less likely to cause numerical problems
  - They are more temperature-stable
    - Very important for upstairs/downstairs calibrations
  - Will give more confidence politically
  - USNO has loaned two for free

Upstairs/Downstairs

- Fiber tempco ~ 15 ps/degC/Km (manufacturer specs)
  - Tempcos may be much higher when jacketed
  - Adjacent fibers experience temperature offsets
  - Diurnal = 30 ps for 100 m * 20 degC (assumed variation)
  - Coax ⇔ Fiber modules have tempcos
- Round-trip correction desirable
- Separate fiber paths for 1-pps and 10 MHz
- USNO plan has redundant uplinks
  - Link calibration can be done by switching components

At The Far Detector



A Brief Overview

GPS PRECISE POINT POSITIONING

What is GPS PPP?

- GPS PPP is a way to use precise ephemerides published by the International GNSS Service (IGS) along with code and carrier phase GPS measurements to compute a precise solution from a single GPS receiver
- Many additional physical effects have to be modeled to achieve a precise, day-to-day repeatable solution

Differences from CORS

- A precise position and timing solution can be computed from a single receiver
- Almost always used after-the-fact
  - Experiments are being conducted on real-time PPP, but the solution takes longer to converge than double-differencing (~30 minutes)
- Many physical phenomena which cancel when double-differencing must be modeled or measured
- Additional error sources such as satellite phase center variations and total group delay differences in satellite and user equipment must be included
- Dependent on IGS orbit and clock products
- Time transfer is possible on much longer baselines!

GNSS Code and Phase

- Two range measurement types in GNSS
- Pseudorange
  - The code measurement
  - Delivered in “chips” at 1.023×10^6 chips/s for L1 C/A
  - 10x that for L2 P(Y) codes
  - Contains a timestamp → is “coded”, hence code
  - Susceptible to multipath interference

GNSS Code and Phase

- Two range measurement types in GNSS
- Carrier phase
  - Phase measurement
  - Not timestamped
  - Delivered at 1,575.42x10^6 Hz for L1, 1227.6x10^6 Hz for L2
  - An order of magnitude (or more) greater precision and multipath resistance!
  - An integer ambiguity exists to relate the code to the carrier, allowing the carrier measurement to be used
    - PPP estimates this ambiguity

PPP Day Boundary Discontinuities

- PPP estimates the ambiguity between the code and the carrier by averaging the corrected code to the carrier
- Code is noisy, the average is not constant day-to-day
  - Different processing techniques can make up for this, such as processing multiple days at a time
- These result in day-boundary discontinuities in PPP solutions

Physical Phenomena

- Solid-earth tides
  - The motion of the Earth around the Sun and the Moon around the Earth also causes motion of the solid earth
  - These motions are very smooth and easy to calculate
  - Can cause diurnals of more than 20 cm (almost 60 cm in Boulder)
- Ocean loading
  - Much like solid-earth tides, the tidal cycle of the ocean can influence a PPP solution, particularly at sites close to the ocean
  - A particularly dramatic location is Cornwall, England, which can move approximately 14 cm in 6 hours!
- Ionospheric delay
  - Can be measured directly with a dual-frequency receiver
- Tropospheric delay
  - Can either be provided or modeled
  - In dual-frequency PPP, the ability to model the troposphere is equivalent to using a measured solution

Additional Error Sources

- Total Group Delay variation among GPS satellites
  - C1→P1 biases: needed for receivers that do not produce a P1 measurement, such as the NovAtel receivers used in the MINOS experiment
  - L1→L2 biases: broadcast TGD value has a noticeable quantization error
- Satellite and User antenna phase center variations
- Satellite clock and position
  - Broadcast messages have a quantization error and become degraded as time passes from uploading

IGS Products

- Precise orbit and clock products
  - Corrects satellite position and clock errors
- Antenna corrections
  - Antenna phase center offsets for GPS/GLONASS satellites and for many GPS antennas

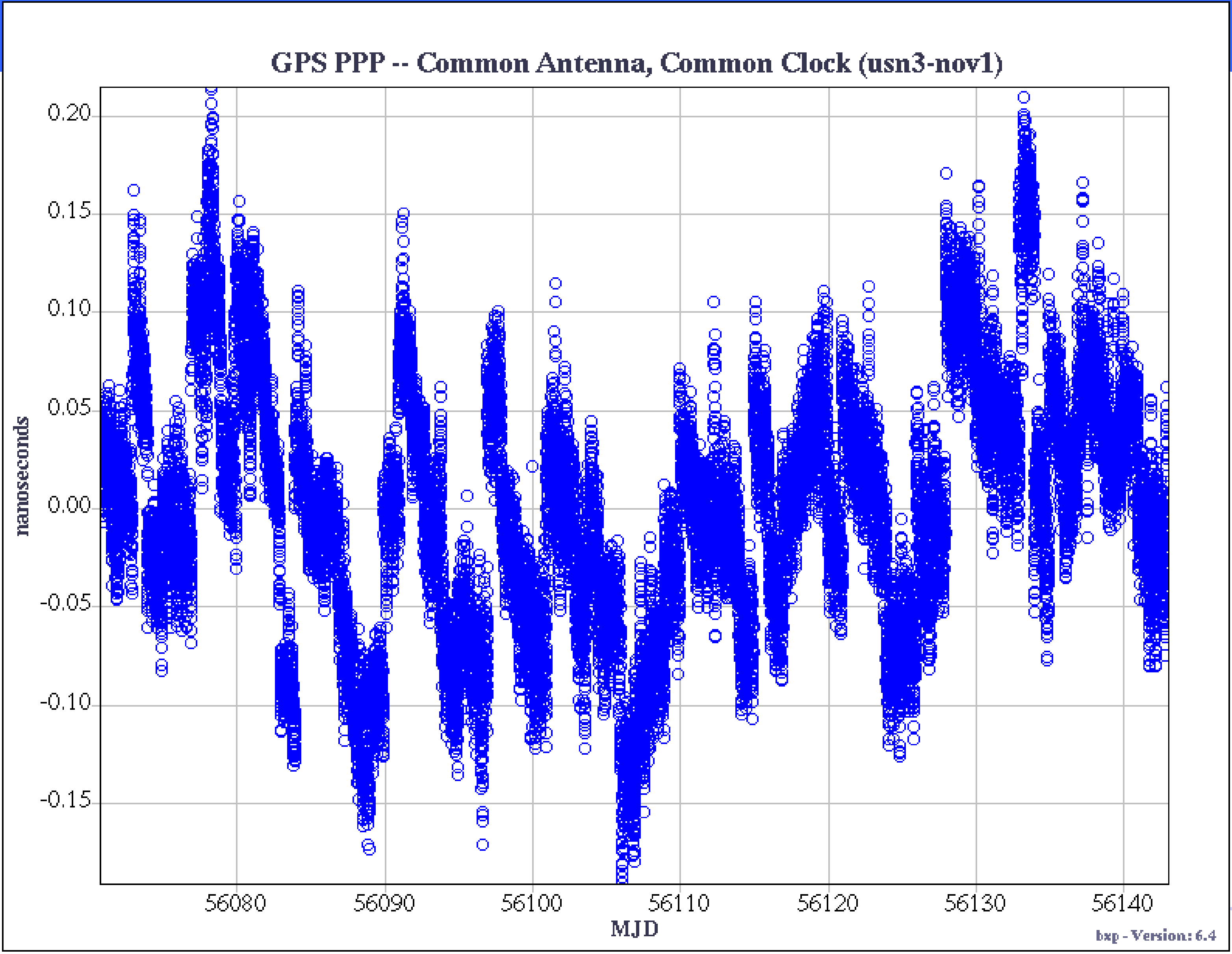
Performance examples of GPS PPP timing solutions

GPS PPP SAMPLE DATA

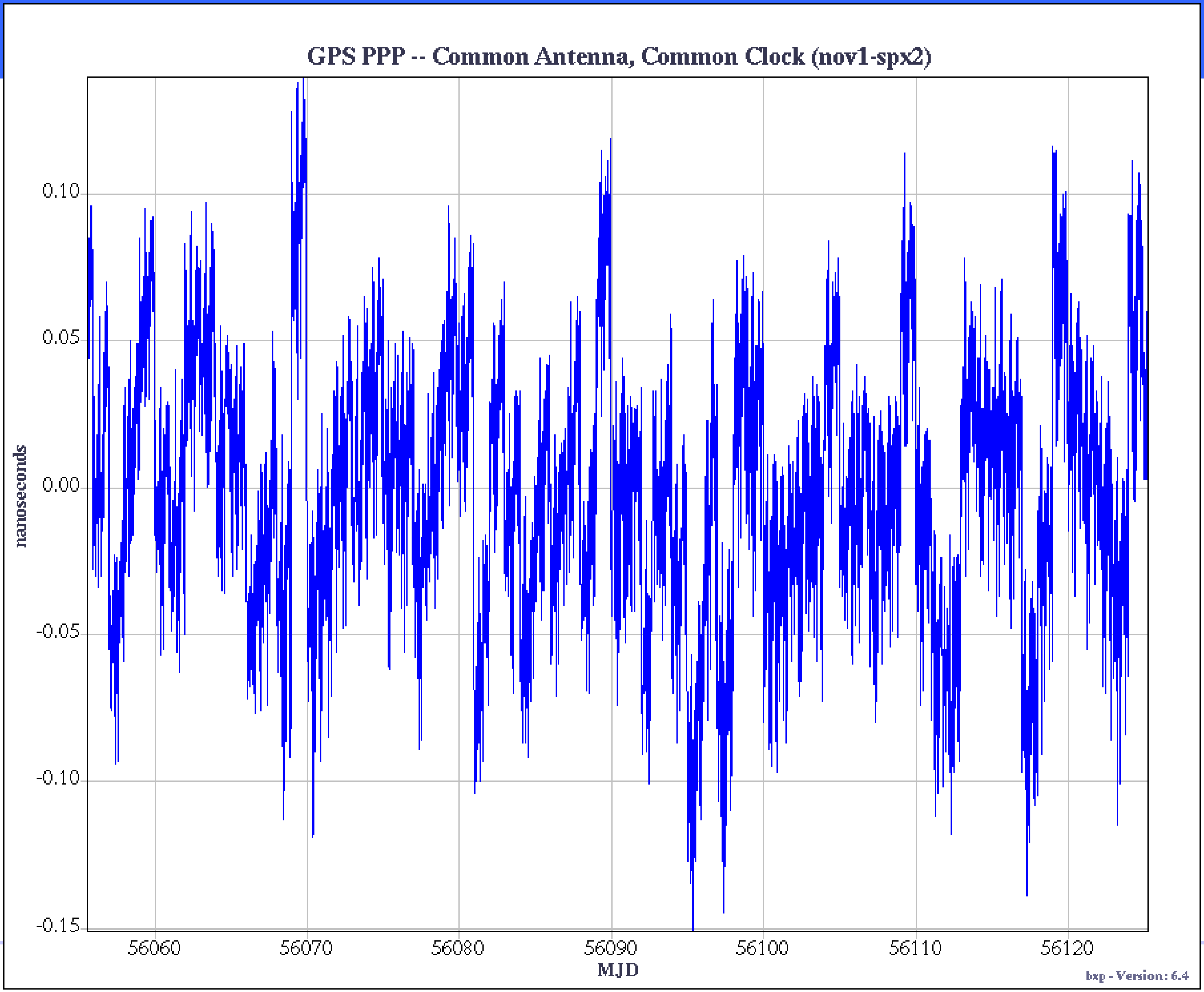
The Method

- PPP processing produces several output files
- One of the files contains the position calculation at each epoch as well as the clock difference from the paper IGS clock
- Take two of these files and difference the clock differences from IGS, and the IGS cancels and you are left with a time difference between two GPS receivers
- Do this for GPS receivers at different locations, and you can effectively transfer time between remote locations without requiring any base stations!

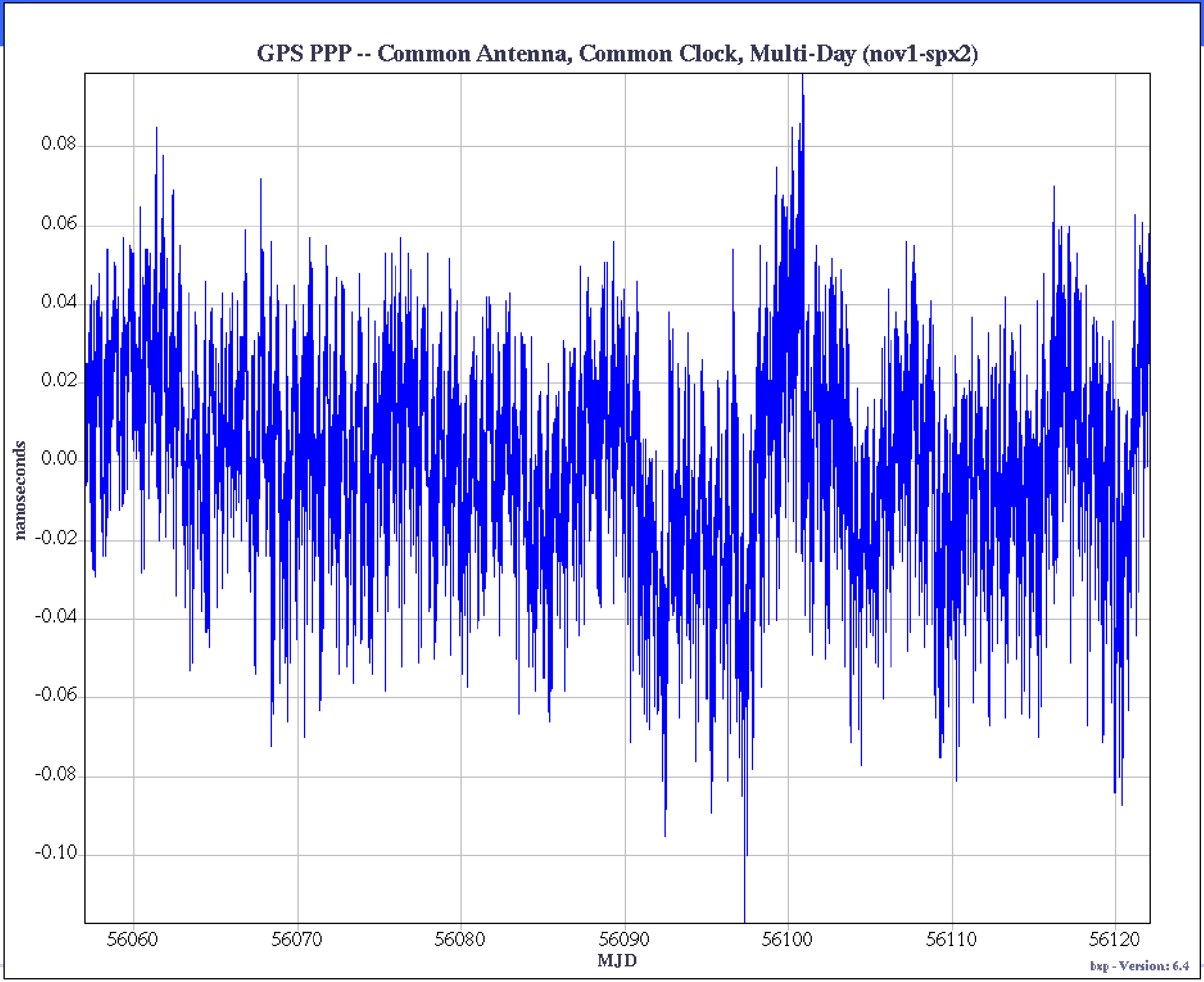
Common Antenna, Common Clock



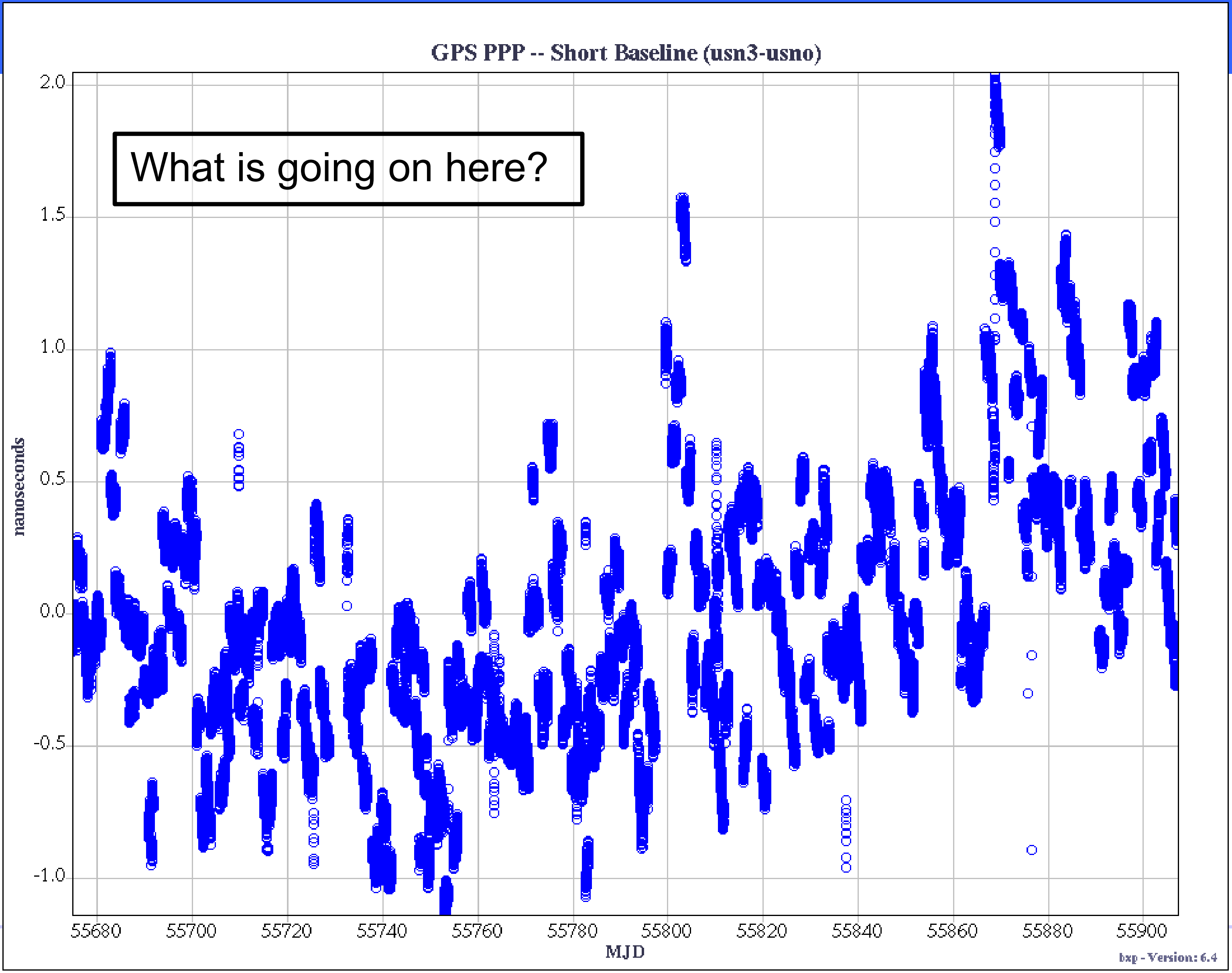
Common Antenna/Clock, Modern Receivers



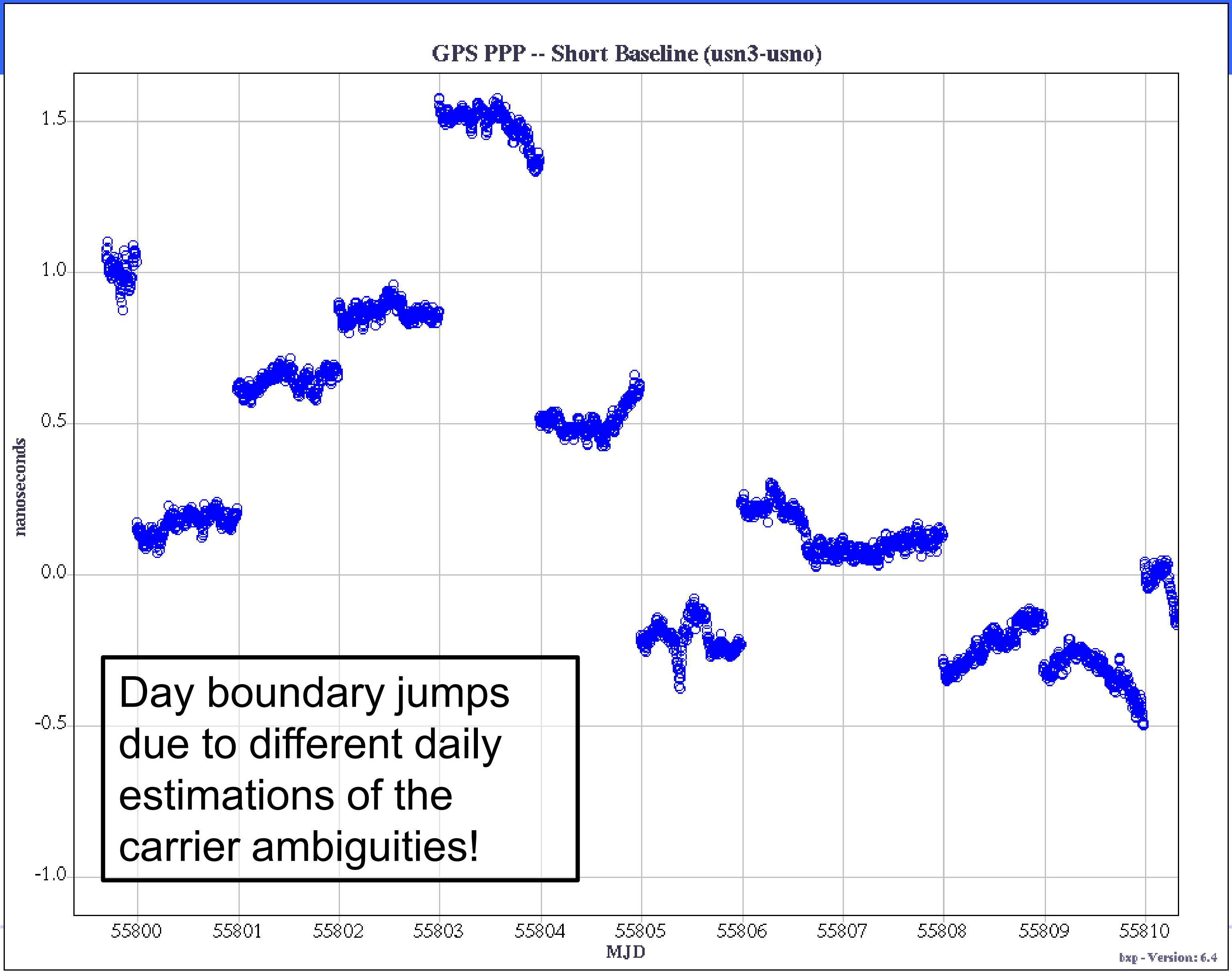
Common Antenna/Clock, Modern Receivers, Multiday Processing



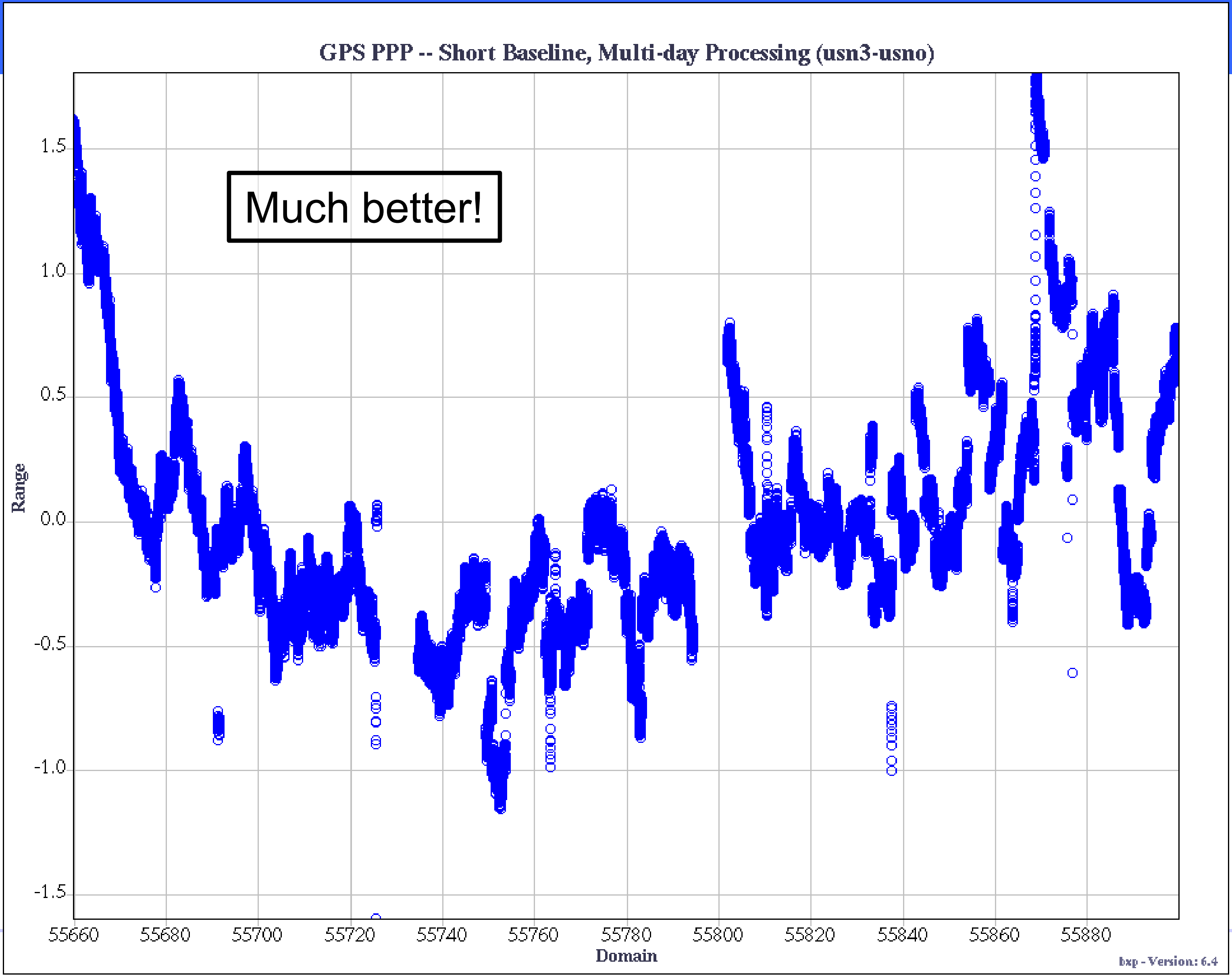
Short Baseline



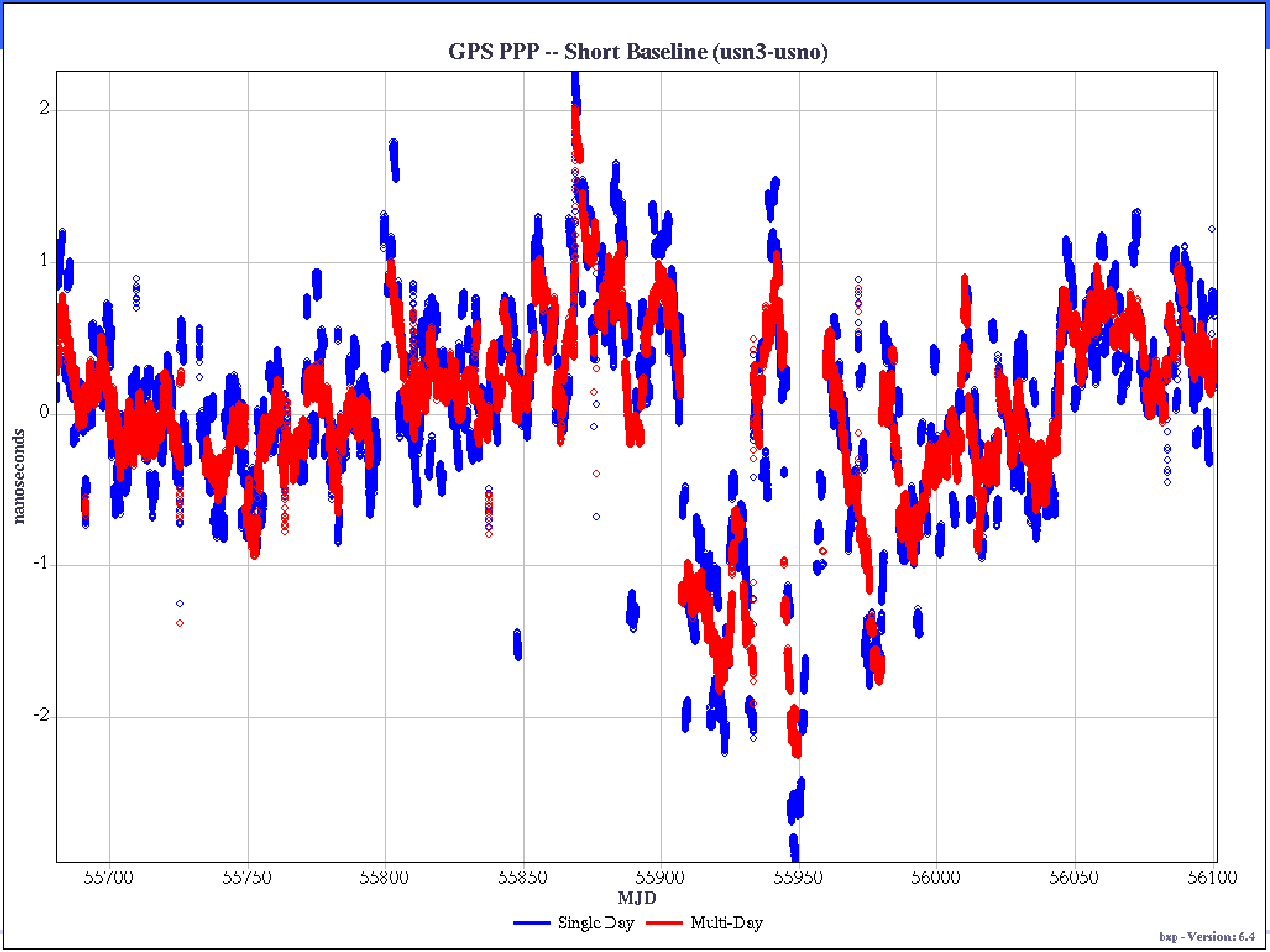
Short Baseline, Zoomed In



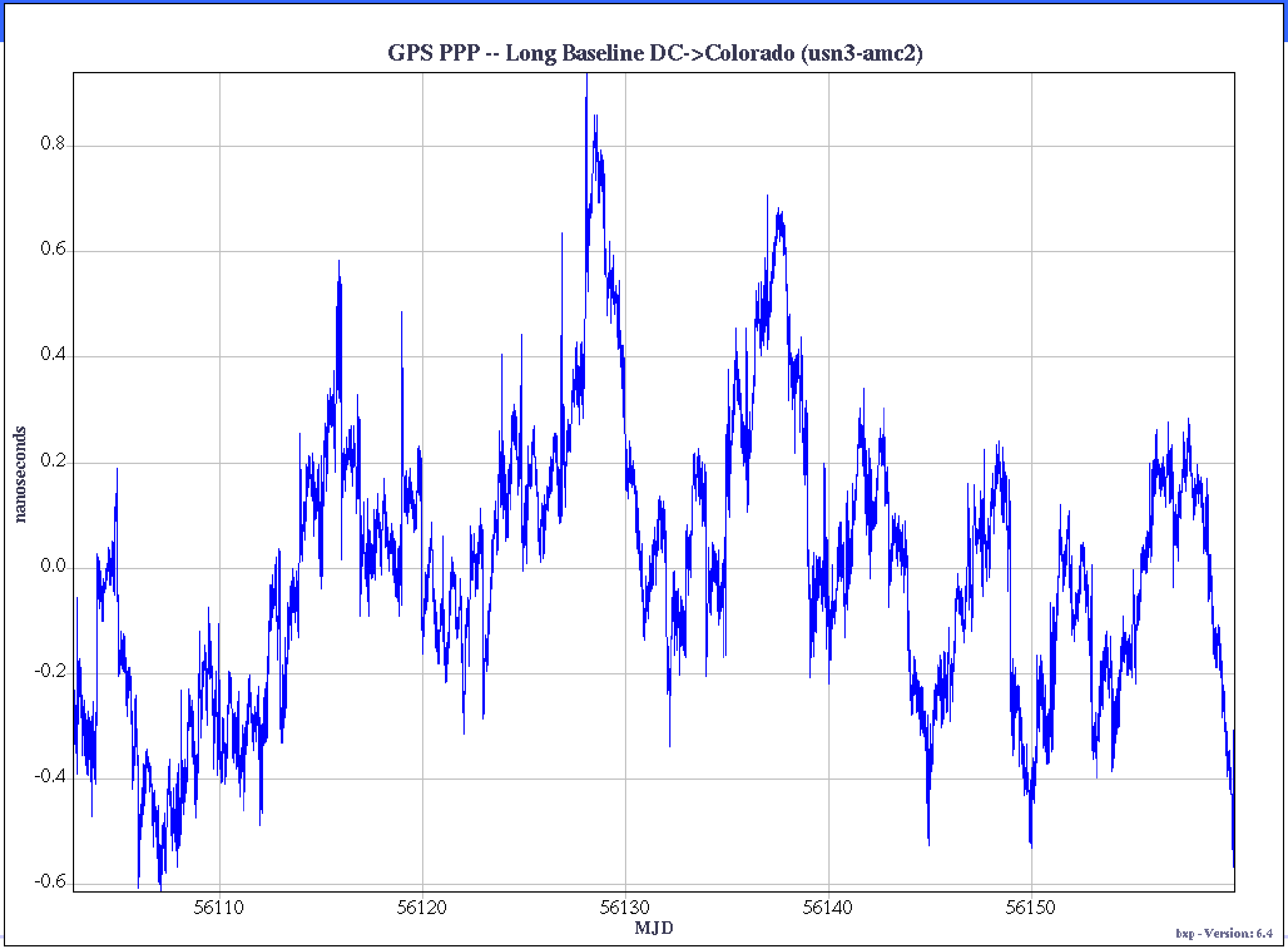
Short Baseline, Multi-Day Processing



Short Baseline, Both Methods

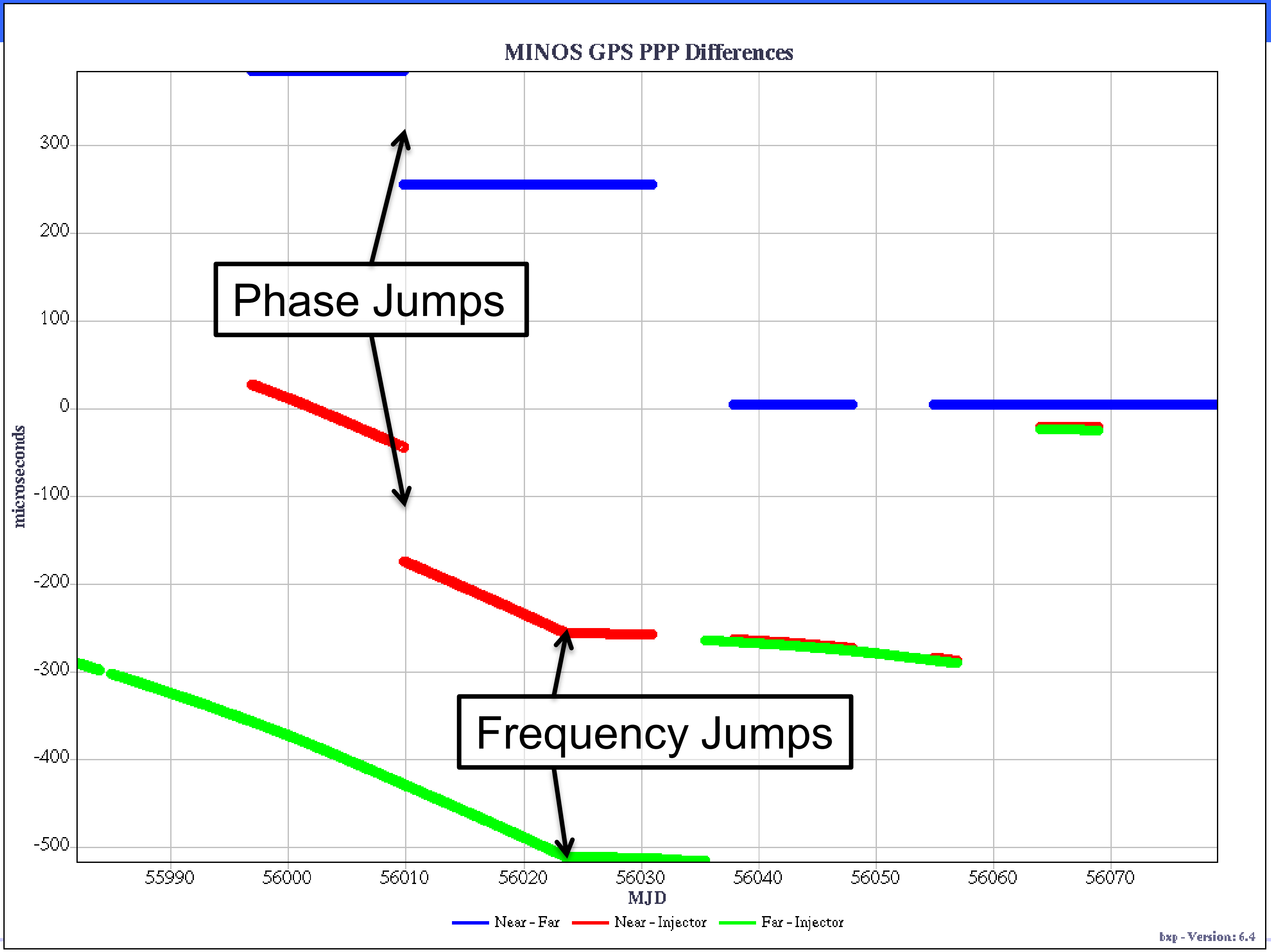


Long Baseline, DC → Colorado

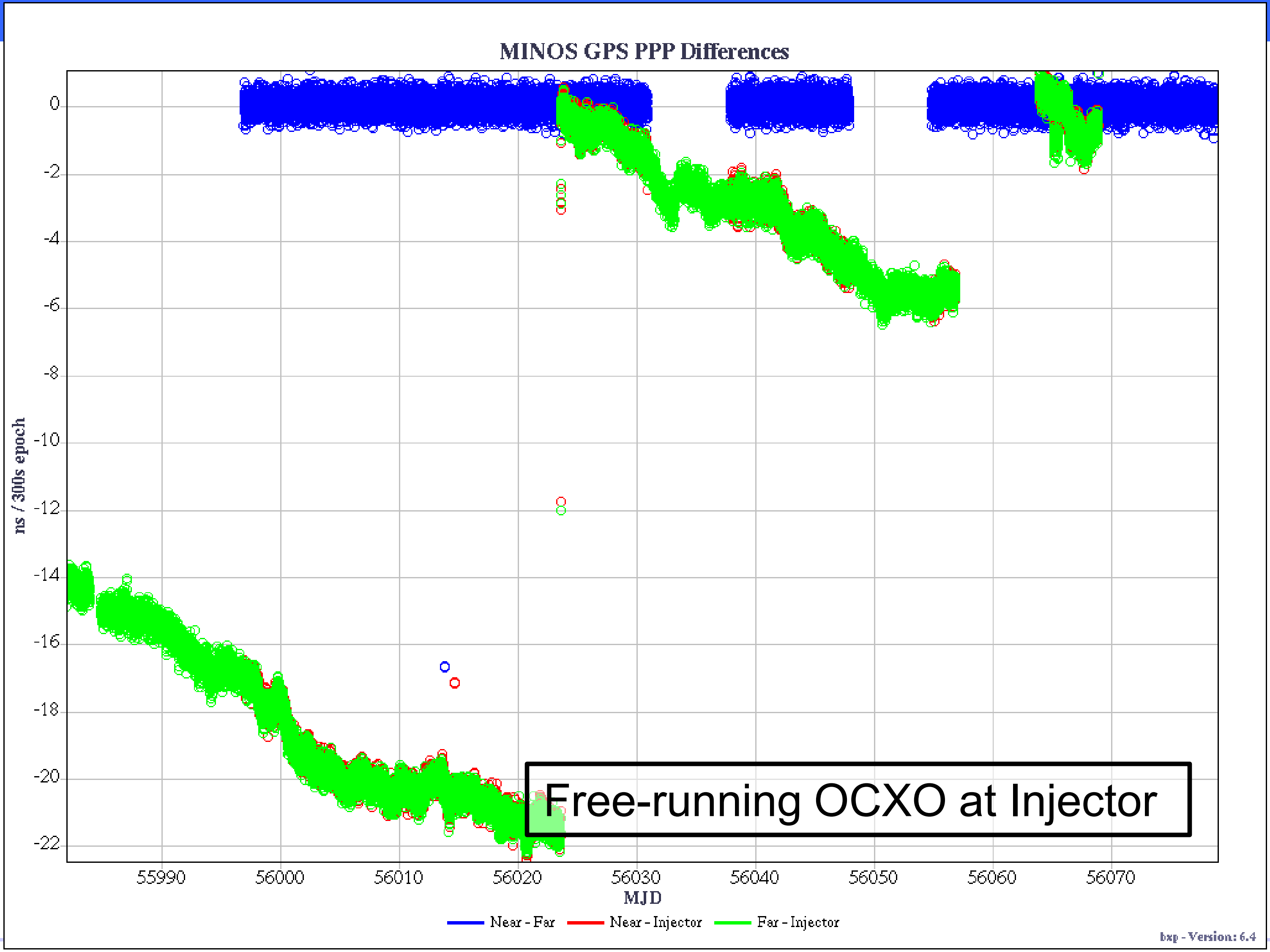


MINOS GPS PPP DATA

MINOS PPP Overview



MINOS PPP Changes Over Time



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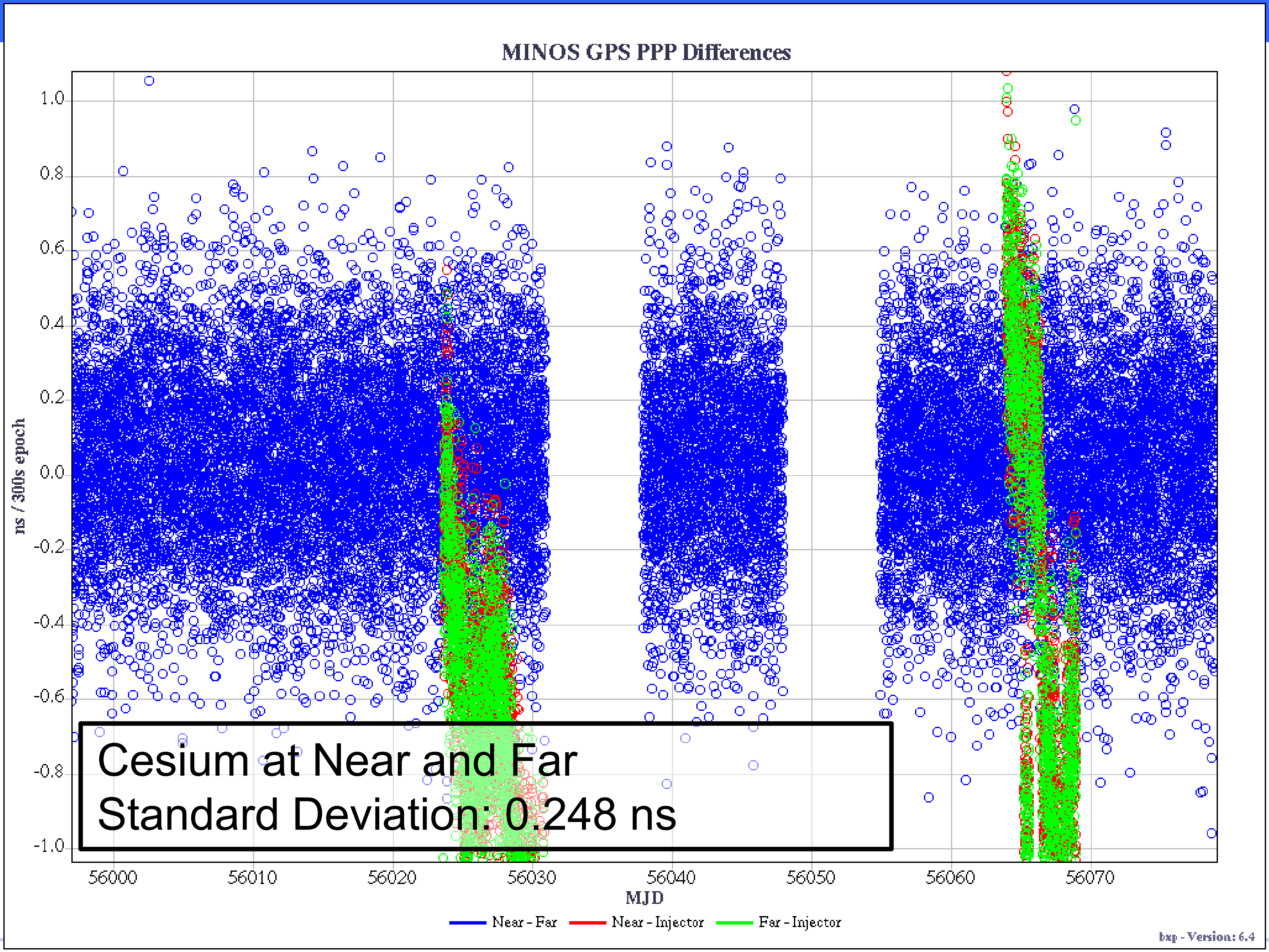

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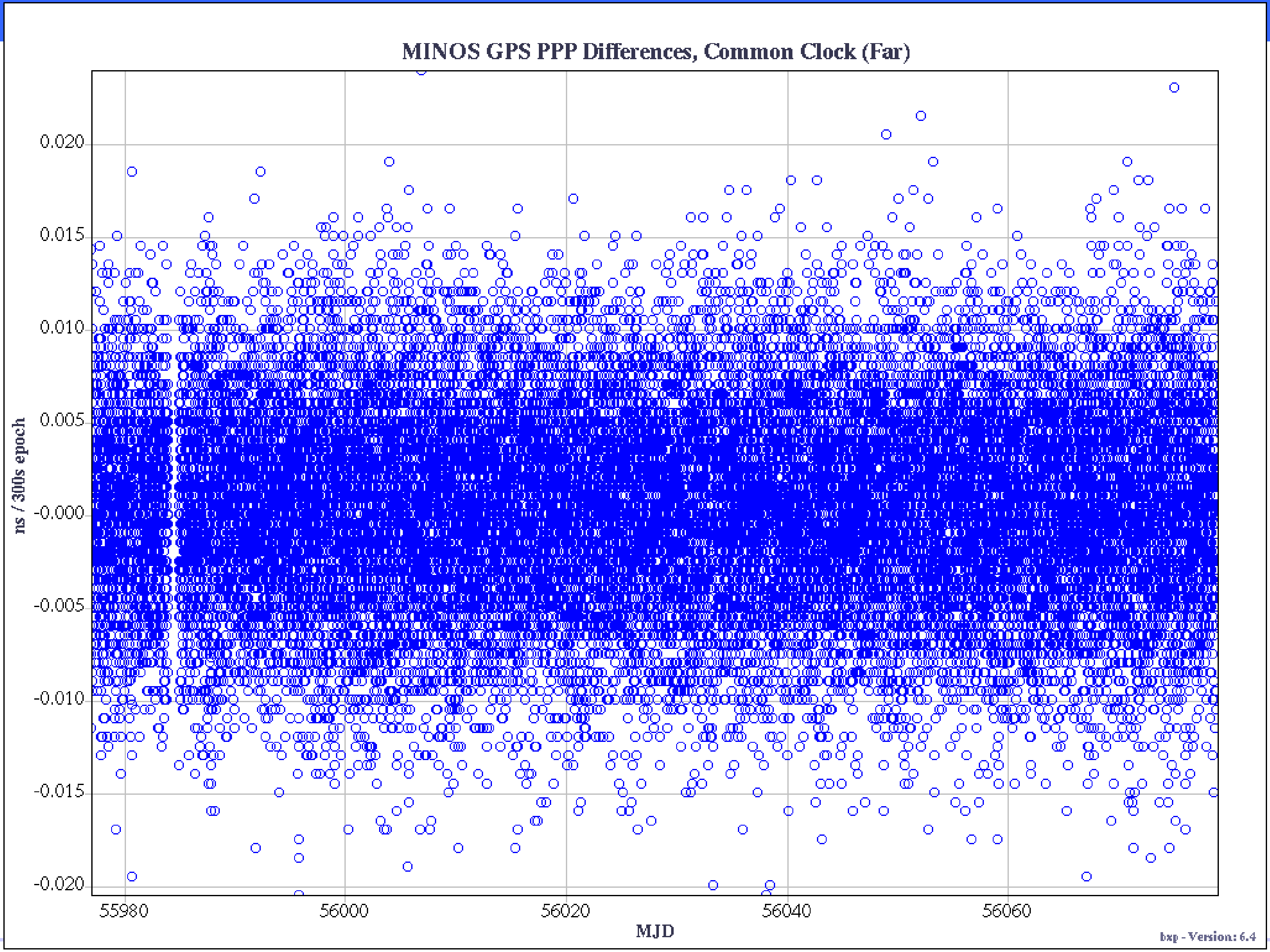
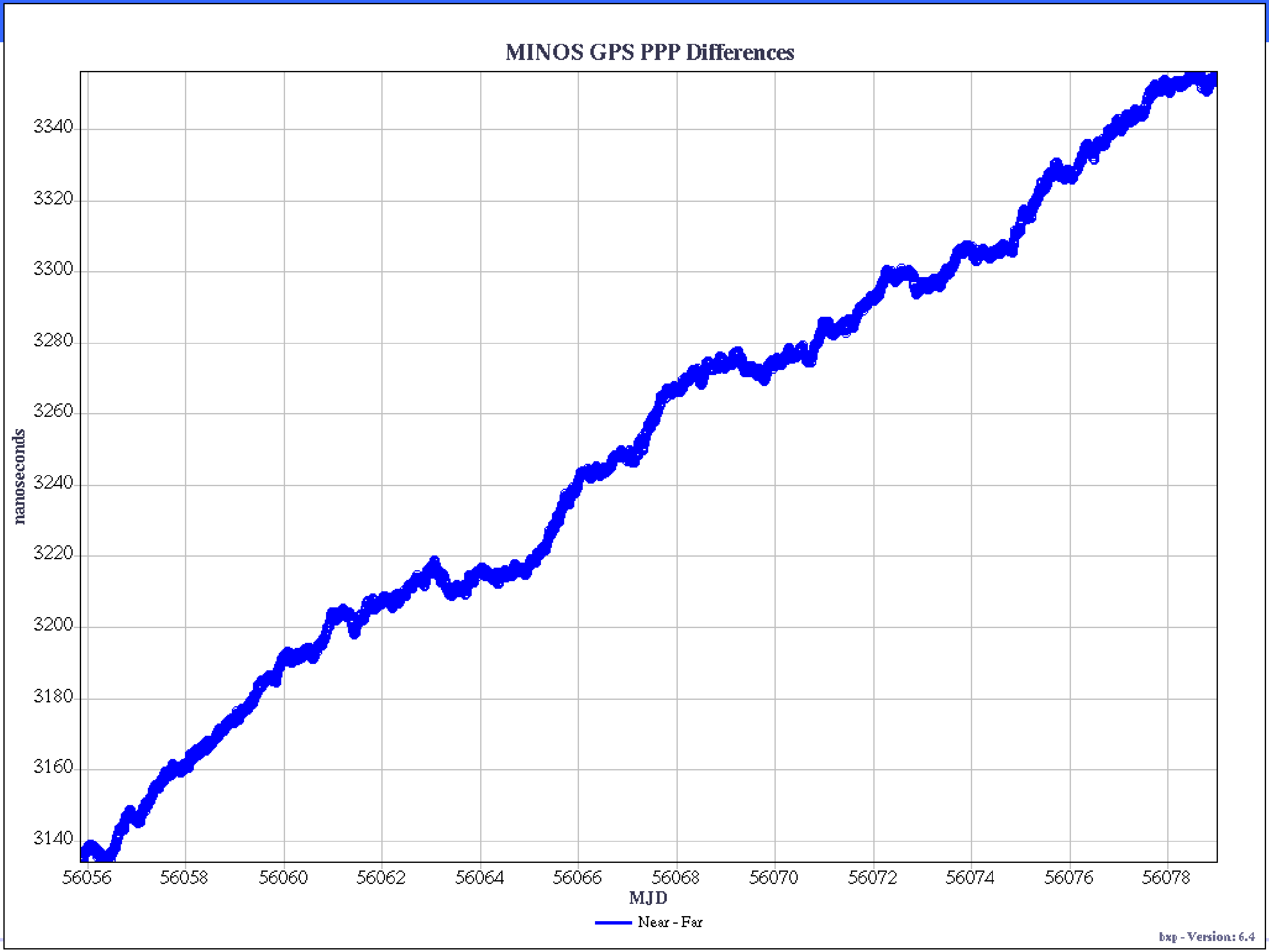
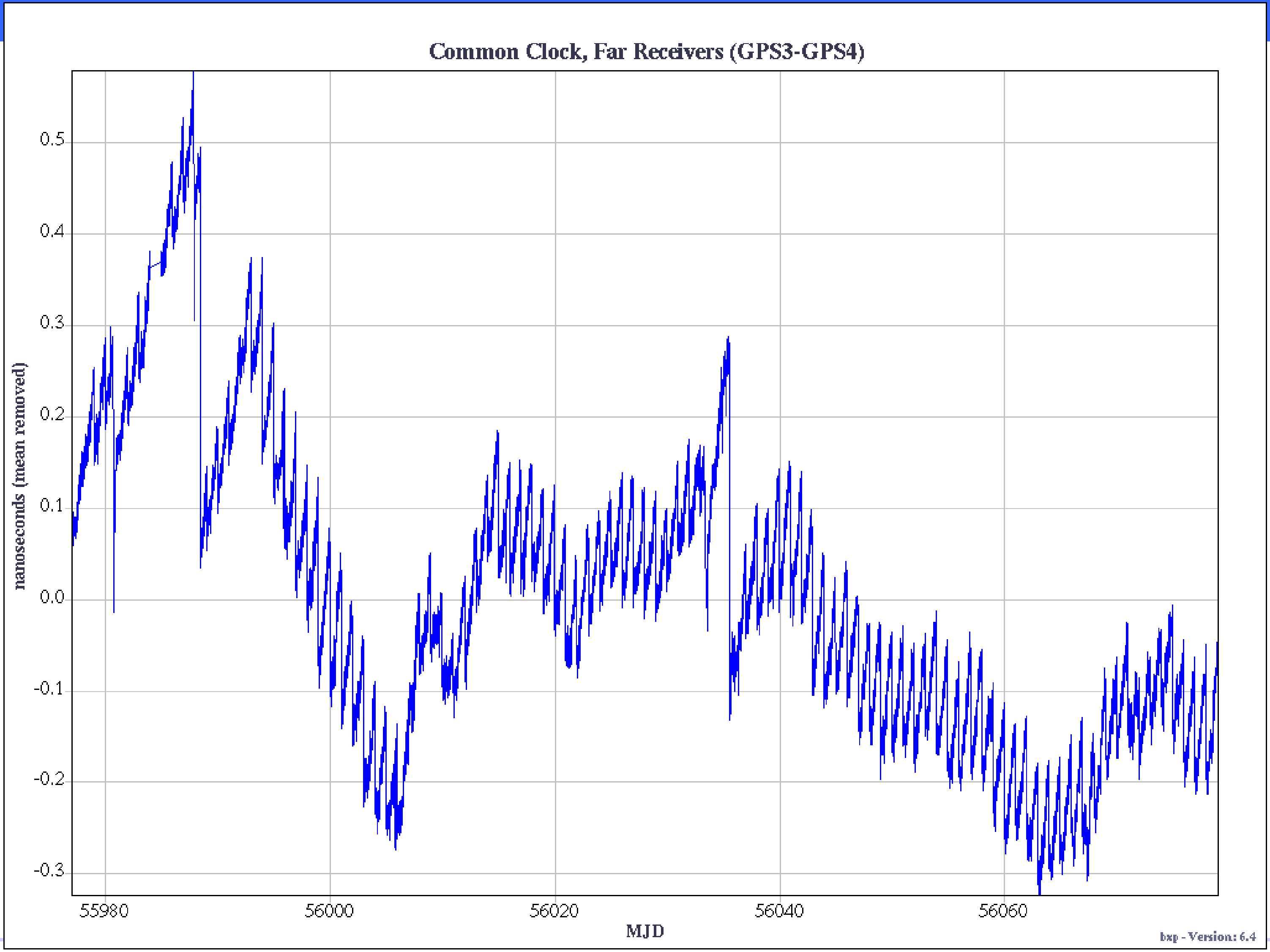


MINOS PPP Near-Far



MINOS PPP Common-Clock



MINOS PPP Time Transfer

- Use traveling receivers to determine systematic differences between the two sites
- Form a calibration value from these systematic differences
- Determine the time difference of the clocks at each site at any given time
- Can use two Time Transfer methods to verify calibration: GPS PPP and Two-Way Satellite Time Transfer

MINOS PPP Time Transfer Traveling Receivers

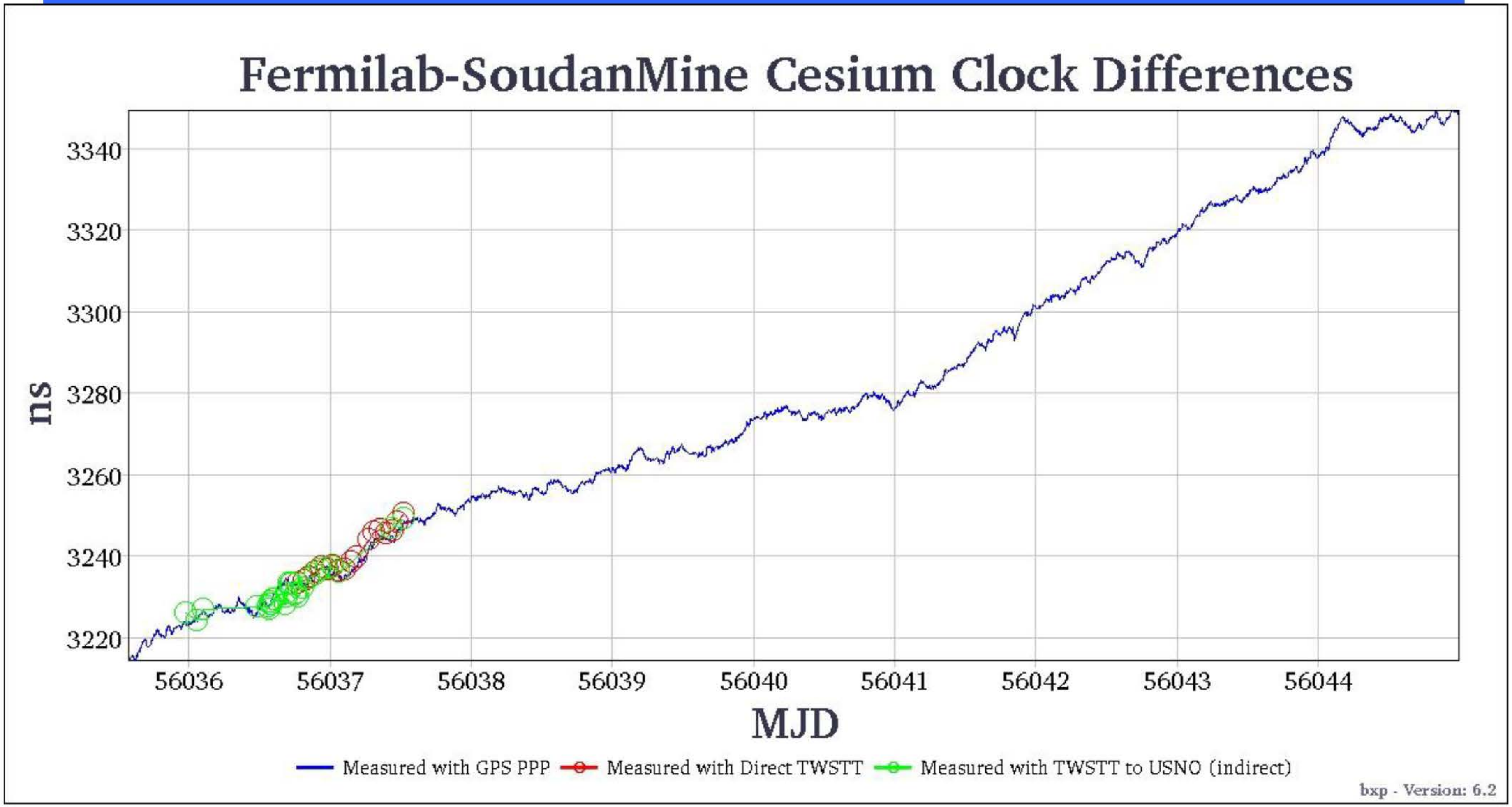
- An entire GPS system consisting of antenna, cables, and receiver
- Everything stays the same between sites except the antenna location and the distribution amplifiers used
- Allows for very precise common-clock comparison to the stationary receivers at each site
- A relative site offset can be determined by comparing the site receivers against the same traveling receiver as it visits each site
- MINOS has two

GPS PPP Calibration Worksheet

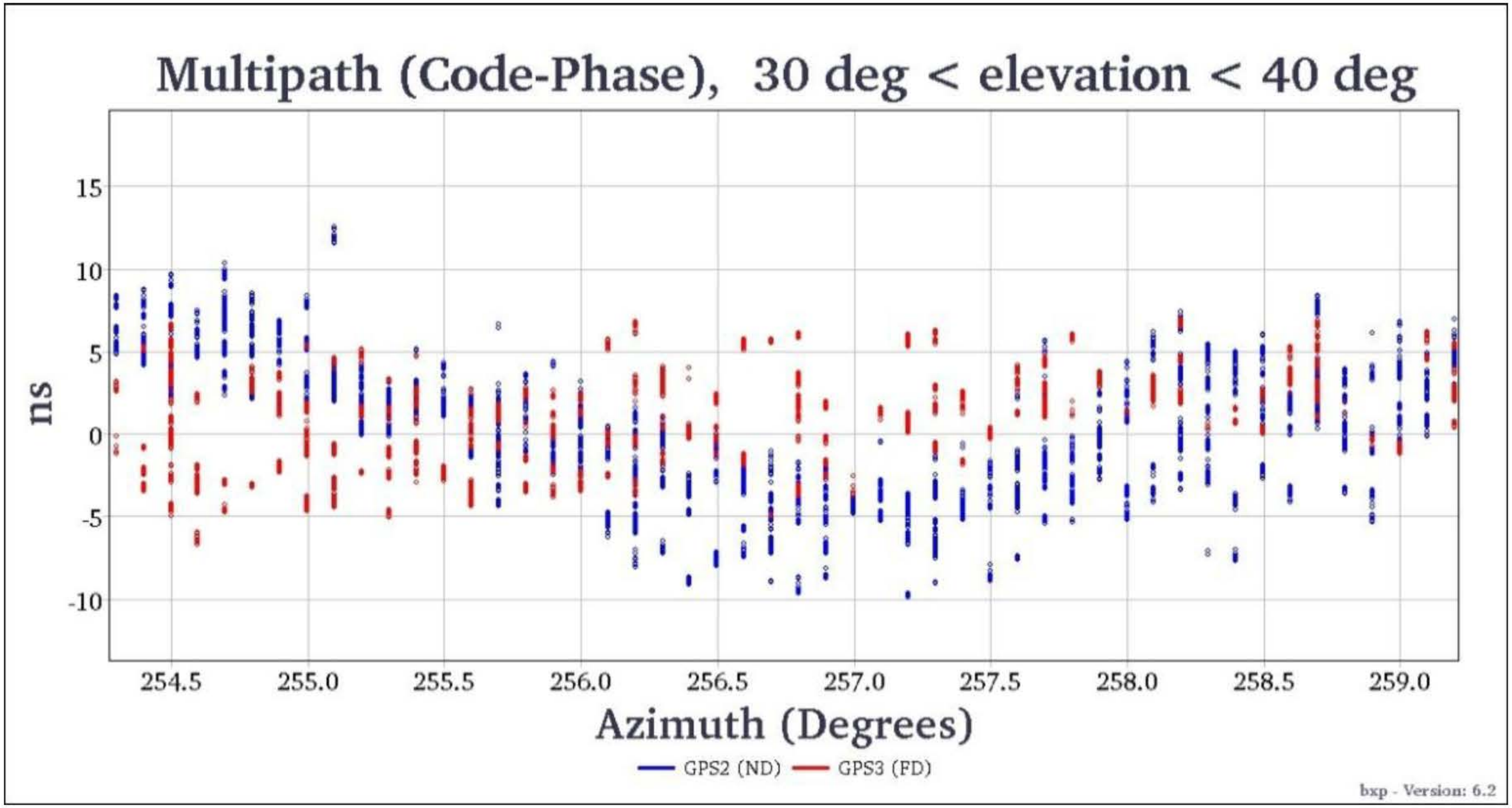
- Apologies for the small text!
- GPS Traveling systems agree to 450 ps!

Minos GPS Time Transfer (PPP)								
Site Name	Character	Role						
Mi60	S	Injector						
Sudan	F	Far Detector (FD)						
FermiLab	N	Near Detector (ND)						
Receiver	GPS1	GPS2	GPS3	GPS4	GPS5	GPS6	GPS7	GPS8
Site	S	N	F	F	Trav	Trav	S	N
	GPS2 (N)	GPS3 (F)	GPS5 (F)	GPS5 (N)	GPS6 (F)	GPS6 (N)		
Tick-to-tick	27.8	14.53	14.31	27.42	14.27	27.39		
*Tick-to-tick added to RCVR-IGS datasets								
Avg GPS5-GPS2	36.62							
Avg GPS5-GPS3	-27.83							
Avg GPS6-GPS2	41.48							
Avg GPS6-GPS3	-23.42							
Double Difference GPS2-GPS3 (via GPS5)				Double Difference GPS2-GPS3 (via GPS6)				
-64.45				-64.9				
Average Double Difference:			-64.675					
Calibration Value to be summed to GPS2-GPS3 Data:								
64.675								
Final Values:	MJD	Value						
	56036.85	3234.07						

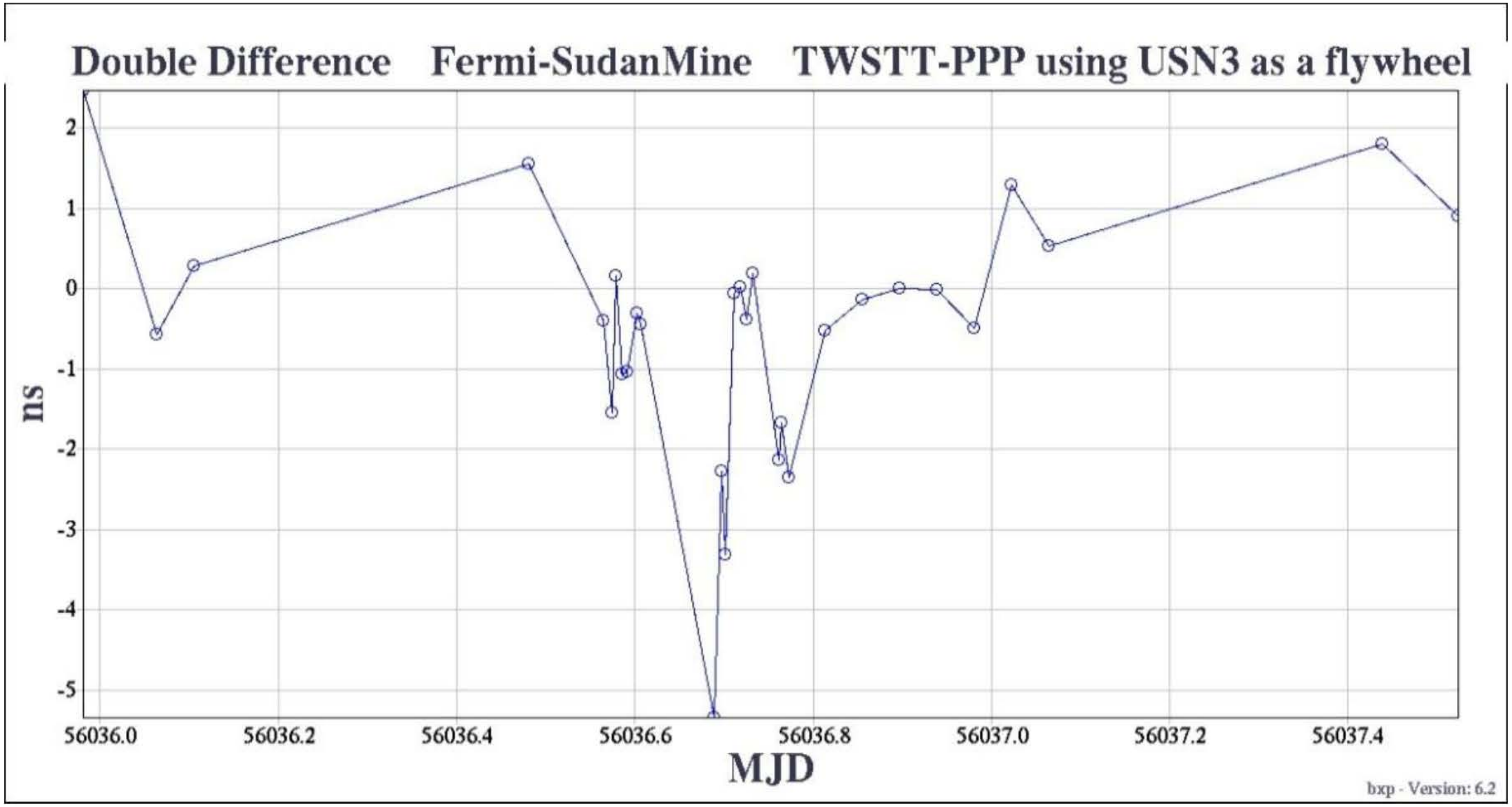
Calibration Works!



Calibration Works?



Calibration Works?



Conclusions

- Time between Near and Far changes by less than 1 ns for each 300s point in the PPP solution (1-sigma: 0.248 ns)
- A Cs atomic clock has 2-sigma instability around 100 ps at 300 s
- Two separate GPS traveling systems had calibrations only 450 ps apart
- Multi-day PPP solutions minimize day-boundary discontinuities
- Relative timing accuracy better than 1 ns*
  - *If the calibration works!

End of Presentation

THANK YOU!